

The blazar sequence: a new perspective

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21 April 2008

ABSTRACT

We revisit the so called “blazar sequence”, which connects the observed bolometric luminosity to the shape of the spectral energy distribution (SED) of blazars. We propose that the power of the jet and the SED of its emission are linked to the two main parameters of the accretion process, namely the mass of the black hole and the accretion rate. We assume: i) that the jet kinetic power is proportional to the mass accretion rate; ii) that most of the jet dissipation takes place at a distance proportional to the black hole mass; iii) that the broad line region exists only above a critical value of the disk luminosity, in Eddington units, and iv) that the radius of the broad line region scales as the square root of the ionising disk luminosity. These assumptions, motivated by existing observations or by reasonable theoretical considerations, are sufficient to uniquely determine the SED of all blazars. This framework accounts for the existence of “blue quasars”, i.e. objects with broad emission lines but with SEDs resembling those of low luminosity high energy peaked BL Lac objects, as well as the existence of relatively low luminosity “red” quasars. Implications on the possible evolution of blazars are briefly discussed. This scenario can be tested quite easily once the *AGILE* and especially the *GLAST* satellite observations, coupled with information in the optical/X-ray band from *Swift*, will allow the knowledge of the entire SED of hundreds (and possibly thousands) blazars.

Key words: BL Lacertae objects: general — quasars: general — radiation mechanisms: non-thermal — gamma-rays: theory — X-rays: general

1 INTRODUCTION

Fossati et al. (1998) studied three complete sample of blazars: the Einstein Slew survey (Elvis et al. 1992), the 1–Jy samples of BL Lacs (Kühr et al. 1981), and the flat-spectrum radio-loud quasars (FSRQs) extracted by Padovani & Urry (1992) from the 2–Jy sample of Wall & Peacock (1985). The total number of studied blazars was 126, and 33 of these were detected in γ -rays by the EGRET instrument onboard the *Compton Gamma Ray Observatory*. These blazars were divided into radio luminosity bins, and the luminosity in selected bands was averaged to form the SED representative of the blazars in each bin. It turned out that the division into radio luminosity bins well matched the division into bins of bolometric luminosity, and that all spectra could be described by two broad peaks, in a νF_ν representation, the first at mm/soft X-rays frequencies, the second in the MeV–GeV band. More importantly, a sequence appeared: blazars with greater bolometric luminosity had “redder” SEDs (i.e. smaller peak frequencies: LBL in the terminology of Padovani & Giommi 1995), and the high energy peak was more prominent. Blazars of lower bolometric luminosity had instead a “blue” SED (HBL in the terminology of Padovani &

Giommi 1995) with the two peaks having approximately the same luminosity.

This spectral sequence was interpreted by Ghisellini et al. (1998) as due to the larger radiative cooling suffered by the emitting electrons of blazars of larger power, where the radiation energy density seen in their comoving frames received a large contribution by photons produced outside the jet. As a model, they adopted a simple leptonic one-zone synchrotron inverse Compton model. In this scenario a stronger cooling resulted in a particle energy distribution with a break at lower energies (producing smaller peak frequencies) with more power emitted through the inverse Compton process (hence the dominance of the high energy peak). This picture was later confirmed (Ghisellini, Celotti & Costamante, 2002; Celotti & Ghisellini 2008) when the new generations of Cherenkov telescopes allowed the detection of an increasing number of low power BL Lacs¹. Through the modelling, the above studies found that there is a good correlation between the energy $\gamma_{\text{peak}} m_e c^2$ of the electrons emitting at the peaks of the SED and the total (i.e. magnetic plus radiative) energy density as seen in the comoving frame of the blazar. Therefore the so called “blazar sequence” comes in two kinds: i) a purely phenomenological sequence, relat-

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¹ see <http://www.mppmu.mpg.de/~rwagner/sources>

ing the SED shape with the bolometric observed luminosity, and ii) a more “theoretical” one, relating γ_{peak} to the amount of radiative cooling. It is clear that the first kind is associated with observed properties: since it considers the brightest blazars, it is likely that it corresponds to the most aligned sources: for blazars that are (even slightly) misaligned, the observed luminosity of an intrinsically powerful source becomes smaller and the observed SED becomes “redder”, contrary to the general sequence. Furthermore, the phenomenological blazar sequence had a rather incomplete SED coverage (only 33 out of 126 sources were observed in the γ -ray band, at that time). Thus, as it stands, the phenomenological blazar sequence probably describes active states of the sources, not necessarily their averaged status.

The second kind, instead, treats comoving quantities and is less permeable to these effects. Since any reasonable blazar luminosity function predicts that the number of blazars increases for decreasing luminosities, one simple prediction of the “theoretical” scheme is that there should be more “blue” blazars than “red” ones.

A critical review of the blazar sequence is presented by Padovani (2007), who pointed out three main tests that the blazar sequence should pass:

- (i) existence of an (anti-)correlation between the synchrotron peak frequency $\nu_{\text{s,peak}}$ and the bolometric observed luminosity;
- (ii) non-existence of “blue” powerful objects;
- (iii) “blue” sources should be more numerous than “red” ones.

Point (i) concerns observed properties: since red low luminosity blazars could be slightly misaligned sources, the existence of red blazar with small observed luminosities is not invalidating the blazar sequence, that even predicts them. The other two points are more important. In general, blazars with emission lines (FSRQs) have larger bolometric luminosities and “red” spectra. However, there are exceptions to this general rule. One example is RGB J1629+4008 (at a redshift $z = 0.272$), discussed in Padovani et al. (2002). This blazar has broad emission lines with equivalent width typical of FSRQs ($\sim 80 \text{ \AA}$), and its synchrotron spectrum peaks at $\sim 10^{16} \text{ Hz}$, that corresponds to a “blue” SED. The luminosity of its broad emission lines is relatively modest ($\sim 7 \times 10^{43} \text{ erg s}^{-1}$); the modelling yields parameters consistent with the “theoretical blazar scheme” (i.e. its γ_{peak} belongs to the correlation found in Ghisellini et al. 1998; see Fig. 9 of in Padovani et al. 2002). Another object showing (weak) broad emission lines and a blue SED is RX J1456.0+5048 ($z = 0.479$)². As discussed in Maraschi et al. (2008) this source is very similar to RGB J1629+4008, and belongs as well to the $\gamma_{\text{peak}}(U')$ correlation.

Padovani et al. (2003) searched for other blue quasars using two large sample of blazars, the Deep X-ray Radio Blazar Survey (DXRBs), and the *ROSAT* All-Sky Survey–Green Bank Survey (RGB), for a total of about 500 sources. They found a relatively large number of possible candidates, but this finding was based on a rather poor characterisation of the SED, parametrised through the radio, optical and X-ray fluxes and the broad band spectral indices connecting the radio to optical (α_{RO}), the optical to X-ray (α_{OX}) and the radio to X-ray (α_{RX}) fluxes. Note that in the absence of multi-band optical data it is rather difficult to disentangle the beamed non-thermal to the accretion disk blue bump continua. For this reason these results were interesting, but uncertain and therefore not conclusive. A small fraction of these

blue quasar candidates, observed at the VLA (Landt, Perlman & Padovani 2006), showed a rather modest core radio luminosity, at the boundary of the FR I and the FR II radio–galaxy division. Of these, 10 sources were observed by *Chandra* (Landt et al. 2008) and showed flat X-ray spectra (i.e. energy spectral index $\alpha_X < 1$), demonstrating that these blue quasars candidates have instead a red SED. Also the Sedentary survey (e.g., Giommi et al. 2005), tuned to find high synchrotron peak sources, has not detected flat spectrum radio quasars.

Recently, two other high redshift and high power blazars were discovered, claimed to be blue quasars candidates: SDSS J081009.94+384757.0 ($z = 3.95$; Giommi et al. 2007) and IGR J22517+2218 ($z = 3.668$; Bassani et al. 2007). Both are characterised by a large X-ray to optical ratio, that could be interpreted as due to a single synchrotron component peaking at X-ray frequencies. This possibility, mentioned in both papers, is disfavoured by the fact that the X-ray spectral slope, in IGR J22517+2218, is flatter than α_{OX} , suggesting that the X-ray flux belongs to the high energy peak. Instead, in SDSS J081009.94+384757.0, the optical flux can correspond to the thermal emission from the accretion disk, and if so, also this source fits very well in the blazar sequence (see the SED and the corresponding model in Fig. 3 of Maraschi et al. 2008).

The two papers mentioned above proposed also that if these sources are indeed red, then they would be the prototype of a new class of blazars with extreme properties, namely a very dominating high energy peak. However, these two sources have a SED that is not unprecedented: the high redshift ($z > 4$) blazars (GB 1428+4217, $z = 4.72$; Fabian et al. 1998; PMN J0525–3343, $z = 4.4$; Fabian et al. 2001; RX J1028.6–0844, $z = 4.276$; Yuan et al. 2000; Q0906+6930, $z = 5.47$; Romani et al. 2004) have a very similar SED, with a similar X-ray to optical flux ratios (see also RBS 315 at $z = 2.69$; Tavecchio et al. 2007). Therefore all these sources are not powerful blue quasars, but the extreme manifestation of the blazar sequence (high energy peak increasingly dominating increasing the observed luminosity; see Maraschi et al. 2008). Far from disproving the blazar sequence, they fully confirm it.

Concerning the third test that the blazar sequence should pass (blue BL Lacs should be more numerous than red blazars), Padovani et al. (2007, see also the review of Padovani 2007) pointed out that the ratio of blue/red counts of BL Lacs in deeper (in flux limit) radio and X-ray samples of blazars disagrees with the predictions made by the Fossati et al. (1997) assuming the blazar sequence. The disagreement is moderate for the X-ray surveys, and is more severe for radio surveys down to the 50 mJy flux level (in the sense that Padovani et al. 2007 find a ratio blue/red BL Lacs a factor ~ 3 smaller than predicted by Fossati et al. 1997).

The possible solution to this problem offered by the blazar sequence is the following: if red blazars are intrinsically more powerful than blue BL Lacs, they can enter a flux limited sample even if the jet is (slightly) misaligned, while blue BL Lacs cannot. This selection effect could make red blazars to be over-represented in the sample. This is admittedly no more than an educated guess, and it should be supported by detailed simulations: Fossati et al. (1997) did not consider slightly misaligned blazars. As discussed below, the blazar sequence we are proposing in this paper can offer an alternative (or additional) explanation to the above problem, in terms of BL Lacs whose black hole has a relatively small mass.

In this paper we try to improve and to extend the blazar sequence, taking into account that

- i) the phenomenological sequence was based on bright sam-

² See the presentation by P. Giommi at <http://www.iasfbo.inaf.it/simbolx/program.php>

ples, and on a few high energy detections, not on the “average” states of typical sources; ii) we now know many more TeV BL Lac objects; iii) we made progress in calculating the power of the jet of blazars; iv) we also made progress in estimating the mass of the central black hole in some blazars.

The old phenomenological sequence was based on only one parameter: the bolometric apparent luminosity. We here explore the possibility to associate the SED of all blazars to the two fundamental parameters of all AGNs: the mass of the black hole M and the accretion rate \dot{M}_{in} . To this aim we build upon the old “theoretical” blazar sequence, driven by a few simple ideas and pieces of evidence:

- There is a preferred region of the jet where most of the observed radiation is emitted (see e.e. Ghisellini & Madau 1996). The location of this region, in the jet, should scale as the mass of the black hole.
- Broad emission lines come from a region whose distance from the black hole scales (approximately, and with some scatter) with the square root of the disk luminosity.
- The broad emission line region exists only if the disk luminosity is above a critical value (in Eddington units).
- The power of the jet (Poynting flux plus kinetic) scales as the mass accretion rate.

We will examine and justify these points in the next section, here we stress only that these main hypotheses will suffice to completely describe the SED produced by the jets of blazars. Therefore we will construct a two-parameter sequence, for which the SED is dependent upon \dot{M}_{in} and M . Since the disk luminosity L_{disk} is univocally determined given \dot{M}_{in} and M , the two parameters can equivalently be L_{disk} and M .

2 ASSUMPTIONS

In this section we discuss the main assumptions of our model.

2.1 Black hole masses

It is generally believed that the black hole mass of a radio-loud AGN is on average larger than the typical mass of a radio-quiet object. However, the exact range of black hole masses of radio-loud AGNs is still a matter of debate.

Lacy et al. (2001) proposed that the radio-loudness is a function of mass, with most radio-loud sources having $M > \text{a few } \times 10^8 M_{\odot}$, while D’Elia et al (2003), with a sample of strong lined blazars, found a range of masses extending significantly to the lower end, down to a few $\times 10^7 M_{\odot}$ (see Metcalf & Magliocchetti 2006 for a recent discussion). In Fig. 1 we show the distributions of masses of FSRQs in the D’Elia et al. (2003) sample and of BL Lac objects (Woo et al. 2005; Wagner 2008), and compare them with the range of black hole masses estimated by Ghisellini & Celotti (2001) for FR I and FR II radio-galaxies. A caveat is in order: the correlations used to calculate the mass (i.e. the mass-bulge optical luminosity, or the size of the broad line region and the line width, or the $\sigma - M$ relation) have a large scatter, and therefore the shown distribution are only approximate. We indicate in the figure the corresponding averages of $\log M$ and their 1σ dispersion. We conclude that most black hole masses are in the range $3 \times 10^7 - 3 \times 10^9 M_{\odot}$, and use this range in the following.

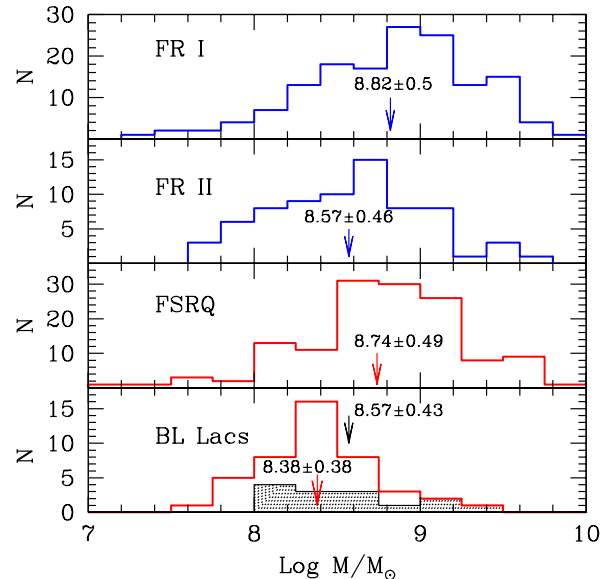


Figure 1. Distribution of black hole masses calculated in Ghisellini & Celotti (2001) for FR I and FR II radio-galaxies (top two panels) by D’Elia et al. (2003) for FSRQs and for BL Lacs by Woo et al. (2005) and Wagner (2008). In the bottom panel the shaded histogram is for TeV BL Lac only. The arrows indicate the average of the logarithm of the masses, as labelled.

2.2 Accretion rates

A natural upper limit is obviously the Eddington one. Another critical accretion rate, probably connected with the change of accretion mode, is for accretion luminosities L_c around a few $\times 10^{-3} L_{\text{Edd}}$. Below this critical values the accretion flow can be advection dominated (Narayan & Yi 1994), or ADIOS (Blandford & Begelman, 1999, 2004), becoming radiatively inefficient, hotter and geometrically thicker. In Ghisellini & Celotti (2001) we have proposed that the dividing line between FR I and FR II (in a radio luminosity vs host galaxy optical luminosity plot) corresponds to this critical value. There also are several evidences that BL Lac objects indeed have radiatively inefficient disks, whose thermal emission is never seen. The absence of a strong ionising luminosity produced by the disk explains in a natural way the absence (or the extreme weakness) of the emission lines in BL Lacs. Also, if this is the reason of the FR I vs FR II and BL Lac vs FSRQ behaviour, there are interesting consequences on the redshift evolution of these classes of sources, since it is conceivable that there is some evolution in the accretion rate (as in radio-quiet quasars), and therefore BL Lacs (low accretion rates) might be more local (no or negative evolution), while FSRQs should be more numerous (and powerful) in the past (positive evolution), as proposed and discussed by Cavaliere & D’Elia (2002) and Böttcher & Dermer (2002), and further discussed below. As a lower limit to the accretion rate we are guided, for instance, by M87, whose disk should emit at $L \sim 10^{-6} L_{\text{Edd}}$. Also with these very small accretion rates, radio-loud systems can produce powerful jets.

To summarise, we will assume that for $L_c/L_{\text{Edd}} < L/L_{\text{Edd}} < 1$ we have “standard” accretion disks which originates the jets in FSRQs (and FR II radio-galaxies), while, for $10^{-6} < L/L_{\text{Edd}} < L_c/L_{\text{Edd}}$ we have BL Lac objects (and FR I radio-galaxies). The exact value of this subdivision (i.e. L_c/L_{Edd}) is not very important, as long as the subdivision exists.

2.3 Seed photons from the Broad Line Region

For our purposes, one important parameter is the radiation energy density of the broad emission line photons. We therefore need to estimate the radius of the broad line region and its total luminosity. We assume that the latter is 10% of the accretion disk luminosity (if this is larger than L_c , see above). For the radius of the BLR there are, in the literature, several proposals:

- according to Kaspi et al. (2005), the relationship between the radius of the BLR R_{BLR} and the ionising disk luminosity is:

$$\frac{R_{\text{BLR}}}{10 \text{ lt days}} = (2.23 \pm 0.21) \left[\frac{\lambda L_\lambda(5100\text{\AA})}{10^{44} \text{ erg s}^{-1}} \right]^{0.69 \pm 0.05} \quad (1)$$

where $L_\lambda(5100\text{\AA})$ is the monochromatic luminosity calculated at 5100 Å.

- Bentz et al. (2006) pointed out a source of uncertainty in this relation associated with the flux of the host galaxy, contributing more at low AGN luminosity. Considering then a sample of AGN observed by HST, they derived:

$$\log R_{\text{BLR}} = (-21.2 \pm 1.7) + (0.518 \pm 0.04) \log [\lambda L_\lambda(5100\text{\AA})] \quad (2)$$

with R_{BLR} in light days and $\lambda L_\lambda(5100\text{\AA})$ in erg s^{-1} .

- More recently, Kaspi et al. (2007) considered the CIV line and the continuum at 1350 Å, deriving:

$$\frac{R_{\text{BLR}}}{10 \text{ lt days}} = (0.17 \pm 0.04) \left[\frac{\lambda L_\lambda(1350\text{\AA})}{10^{43} \text{ erg s}^{-1}} \right]^{0.52 \pm 0.04} \quad (3)$$

Note that the last two relations have consistent slopes, but inconsistent normalisations if λL_λ at 1350 and 5100 Å is similar.

Given the above uncertainties, we chose to assume the simplest hypothesis, which is a BLR radius scaling with the square root of the disk luminosity. Also, for simplicity, we use the bolometric disk luminosity, by assuming:

$$R_{\text{BLR}} = 10^{17} L_{\text{disk},45}^{1/2} \text{ cm} \quad (4)$$

This implies that the energy density of the line photons (for an observer at rest with the black hole) is constant:

$$U_{\text{BLR}} = 0.1 \frac{L_{\text{disk}}}{4\pi R_{\text{BLR}}^2 c} = 2.65 \times 10^{-2} \text{ erg cm}^{-3} \quad (5)$$

where we have also assumed a covering factor equal to 10%. Following Ghisellini & Madau (1996), we then assume that the observer comoving with the jet emission region measures U'_{BLR} given by

$$U'_{\text{BLR}} = \frac{17}{12} \Gamma^2 U_{\text{BLR}} = 3.76 \times 10^{-2} \Gamma^2 \text{ erg cm}^{-3} \quad (6)$$

The spectrum of this component is the sum of Doppler broadened lines and a continuum. The most prominent contribution comes from the Ly α line, and this spectrum can be well approximated by a blackbody, with a peak (in νF_ν , in the comoving frame) around $2 \times 10^{15} \Gamma \text{ Hz}$ (see Tavecchio & Ghisellini 2008 for a detailed discussion).

2.4 Seed photons from the pc-scale dusty torus

In the unification scenarios for Seyfert 1 and Seyfert 2 AGNs, one assume the presence of a torus, at pc-scale distances, that blocks the broad line photons to observers at large viewing angles, and absorbs low energy X-ray photons, making the received X-ray spectrum very hard. Crucial to explain the X-ray background (Setti &

Woltjer 1989; Madau, Ghisellini & Fabian 1994), the dusty torus could be present also in jetted sources, but probably only in FR II radio-galaxies (and FSRQ), since, in FR I radio-galaxies, the very nucleus is not hidden in the optical (Chiaberge, Capetti & Celotti 1999). The possible importance of IR radiation from the torus for the inverse Compton emission of blazars has been pointed out by Błażejowski et al. (2000) (see also Sikora et al. 2002, 2008).

The torus reprocesses the absorbed disk radiation into the IR band. The typical temperature is around 150–200 K (Cleary et al. 2007), as indicated by recent *Spitzer* observations. We approximate the result of Cleary et al. (2007) by assuming that the torus reprocesses half of the disk radiation (corresponding to a opening angle of 60°). The typical distances of the torus, R_{IR} , is assumed to scale as $L_{\text{disk}}^{1/2}$, yielding a constant temperature ($\propto L/R_{\text{IR}}^2$). From the result of Cleary et al. (2007) we then set:

$$R_{\text{IR}} = 2.5 \times 10^{18} L_{\text{disk},45}^{1/2} \text{ cm} \quad (7)$$

The corresponding radiation energy density, as measured in the comoving frame, is

$$U'_{\text{IR}} = 3 \times 10^{-4} \Gamma^2 \text{ erg cm}^{-3} \quad (8)$$

The spectrum of this component is assumed to be a blackbody, with a peak in the comoving frame (in a νF_ν plot) at $3 \times 10^{13} \Gamma \text{ Hz}$.

2.5 Location of the jet dissipation region

We assume that the dissipation radius R_{diss} scales as the Schwarzschild radius R_s : $R_{\text{diss}} = a R_s$, because this scaling is appropriate both in the case of an accelerating jet and in the scenario of internal shocks (Sikora, Begelman & Rees 1994; Ghisellini 1999; Spada et al. 2001) where we have

$$R_{\text{diss}} \sim \Gamma^2 R_0 \sim a(\Gamma) R_s \quad (9)$$

where R_0 is the initial separation of two consecutive shells, which can be approximated as a multiple of the Schwarzschild radius. We allow ourselves to have a different factor a for BL Lacs and for FSRQs, to mimic the possibility to have two different origin for the main dissipation in these two classes of objects: namely, in BL Lacs, we could have a standing shock at some radial distance from the black hole (along the lines of Sokolov, Marscher & McHardy 2004). Even in this case we assume that this distance is proportional to the black hole mass, but not necessarily with the same constant as in FSRQs.

The size of the emitting region is assumed to be a cylinder of cross sectional radius $r = \psi R_{\text{diss}}$ and height $\Delta R' = r$, as measured in the comoving frame. Here ψ is the opening angle of the jet.

2.6 The jet power

We will base our considerations upon the results presented in Celotti & Ghisellini (2008). In that work we found that the jet power L_j in blazars is dominated by the protons associated to the emitting electrons. We showed that the jet Poynting flux is smaller, and also that the component of the jet power possibly transported by electron positron pairs cannot be dynamically important (see also Sikora & Madejski 2000, Maraschi & Tavecchio 2003). In blazars the thermal component due to the accretion disk luminosity is often hidden by the Doppler boosted non-thermal continuum of the jet, but in FSRQs the presence of the broad emission lines allows to estimate the disk luminosity. We found that the power

of jets is comparable, and often larger than the luminosity emitted by the accretion disk in FSRQs. This is even more true in BL Lac objects, where the disk radiation is almost always invisible.

Based on these considerations, we propose the following *ansatz*: the jet power is always linked with the accretion rate, namely we can write, both for BL Lacs and FSRQs:

$$L_j = \eta_j \dot{M}_{\text{in}} c^2 \quad (10)$$

Since $L_{\text{disk}} = \eta \dot{M}_{\text{in}} c^2$, the jet power can always be written as

$$L_j = \frac{\eta_j}{\eta} L_{\text{disk}} \quad (11)$$

If we set, in FSRQs, the jet efficiency factor η_j equal to the disk accretion efficiency η (in the standard accretion mode, i.e. $\eta_j = \eta \sim 0.1$), we have $L_j = L_{\text{disk}}$. If, as it seems the case (Celotti & Ghisellini 2008; Maraschi & Tavecchio 2003) the jet power exceeds the disk luminosity, then $\eta_j > \eta$.

We assume that the accretion rate in BL Lac objects is below a critical value, \dot{M}_c , at which the accretion flow changes regime from “standard” disk accretion to ADAF-like or ADIOS-like regimes, for which $L_{\text{disk}} \propto \dot{M}_{\text{in}}^2$ (e.g., Narayan, Garcia & McClintock 1997).

We must then relate \dot{M}_{in} with the disk luminosity and then relate the disk luminosity with the jet kinetic power. Since at \dot{M}_c the two accretion regimes corresponds to the same $L_{\text{disk}} = L_c$, we have

$$\begin{aligned} \eta &= 0.1; & \dot{M}_{\text{in}} \geq \dot{M}_c \text{ or } L_{\text{disk}} \geq L_c \\ \eta &= 0.1 \frac{\dot{M}_{\text{in}}}{\dot{M}_c}; & \dot{M}_{\text{in}} < \dot{M}_c \text{ or } L_{\text{disk}} \leq L_c \end{aligned} \quad (12)$$

where we set $L_c = \eta \dot{M}_c c^2$.

The above assumptions allows to consider L_{disk} (or L_j) as the other key parameter, beside the black hole mass, instead of \dot{M}_{in} . The obvious advantage is that both L_{disk} and L_j can be derived (or even directly observed, in the case of L_{disk} of FSRQs) in a much easier way than \dot{M}_{in} .

The above *ansatz* implies that the outflowing mass rate can be found through

$$L_j = \Gamma \dot{M}_{\text{out}} c^2 \rightarrow \dot{M}_{\text{out}} = \frac{\eta_j}{\Gamma} \dot{M}_{\text{in}} \quad (13)$$

2.7 Jet Poynting flux and kinetic power

We assume that a fraction ϵ_B of L_j is in the form of Poynting flux. This allows us to estimate the magnetic energy density as:

$$L_B = \epsilon_B L_j = \pi \psi^2 R_{\text{diss}}^2 U_B \Gamma^2 c \rightarrow U_B = \frac{\epsilon_B L_j}{\pi \psi^2 R_{\text{diss}}^2 \Gamma^2 c} \quad (14)$$

We assume that a fraction ϵ_e is converted, at R_{diss} , in relativistic electrons. Their energy density, calculated in the comoving frame, is $U_e \equiv m_e c^2 \int N(\gamma) d\gamma$ and is given by

$$L_e = \epsilon_e L_j \rightarrow U_e = \frac{\epsilon_e L_j}{\pi \psi^2 R_{\text{diss}}^2 \Gamma^2 c} \quad (15)$$

In fast cooling (i.e. when all the injected electrons can cool in one light crossing time) all the power in electrons is converted into radiation. In slow cooling, instead, only a fraction ϵ_A can be emitted. Therefore we have that the energy density of the radiation produced by the jet is

$$U_r = \epsilon_A U_e = \frac{\epsilon_e \epsilon_A L_j}{\pi \psi^2 R_{\text{diss}}^2 \Gamma^2 c} \quad (16)$$

In our scenario ϵ_e and ϵ_B are free parameters, while ϵ_A can be derived, as described in the Appendix. In Celotti & Ghisellini (2008) ϵ_B and ϵ_e have been found (through spectral modelling) for a sample of BL Lacs and FSRQs detected in γ -rays. It was found that there exists a good correlation between ϵ_e and L_j , and a much more scattered correlation (or trend) between ϵ_B and L_j . Using the relations found in that paper, we here set:

$$\epsilon_e \sim 0.1 L_{j,45}^{-0.4} \quad (17)$$

$$\epsilon_B \sim 0.05 L_{j,45}^{-0.25} \quad (18)$$

2.8 Energy of the electrons emitting at the peaks of the SED

Let us call γ_{peak} the random Lorentz factor of the electrons emitting at the two peaks of the SED. We take advantage of the observed correlation between γ_{peak} and the (comoving) energy density $U'(\gamma_{\text{peak}})$ that is the sum of the magnetic and radiation energy density integrated up to $\nu = m_e c^2 / (h \gamma_{\text{peak}})$. In other words, $U'(\gamma_{\text{peak}})$ is the sum of the magnetic and the radiation energy density available for scattering in the Thomson regime (i.e. efficient cooling). This correlation (updated in Celotti & Ghisellini 2008) is of the form

$$\begin{aligned} \gamma_{\text{peak}} &= 10^3 \left(\frac{U'}{0.3} \right)^{-1}; & U' \leq 0.3 \text{ erg cm}^{-3} \\ \gamma_{\text{peak}} &= 10^3 \left(\frac{U'}{0.3} \right)^{-1/2}; & U' \geq 0.3 \text{ erg cm}^{-3} \end{aligned} \quad (19)$$

In Ghisellini et al. (2002) we have interpreted this correlation (found by modelling SEDs of blue BL Lac objects) as the result of the radiative cooling occurring in one light crossing time. In this time electrons cool down to an energy γ_c given by

$$\gamma_c = \frac{3m_e c^2}{4\sigma_T \Delta R' U'} \propto U'^{-1} \quad (20)$$

This scaling stops when $\gamma_c < \gamma_1$, because in this case the peak (in νF_ν) is produced by electrons at γ_1 . According to Celotti & Ghisellini (2008), this occurs when $\gamma_c \sim 10^3$. For larger energy densities, the scaling $\gamma_{\text{peak}} \propto U'^{-1/2}$ suggests that it is the cooling rate (at γ_{peak}) which is constant, i.e. $\dot{\gamma} \propto \gamma_{\text{peak}}^2 U'$ is the same for all powerful blazars. Note, however, that the scatter in the region of large U' is large, making this relation true only approximately.

2.9 The emitting particle distribution

The energy distribution of the emitting particles, $N(\gamma) [\text{cm}^{-3}]$, is assumed to be the same as the one described in Ghisellini, Celotti & Costamante (2002) and Celotti & Ghisellini (2008). This distribution approximates the case of an injection of particles, throughout the source, lasting for a finite injection time, equal to $t_{\text{inj}} = \Delta R' / c = \psi R_{\text{diss}} / c$. This is because blazars are variable (flaring) sources, and a reasonably good representation of the observed spectrum can be obtained by considering the particle distribution at the end of the injection. When the injection stops, particles above γ_c have cooled, modifying the energy distribution of the injected particles. The latter is assumed to be a broken power-law with slopes $\propto \gamma^{-1}$ and $\propto \gamma^{-s}$ below and above the break at γ_{inj} . We assume that $2 < s < 3$. In the case of fast cooling, occurring when $\gamma_c < \gamma_{\text{inj}}$, we have:

$$\begin{aligned} N(\gamma) &\propto \gamma^{-(s+1)}; & \gamma > \gamma_{\text{inj}} \\ N(\gamma) &\propto \gamma^{-2}; & \gamma_c < \gamma < \gamma_{\text{inj}} \end{aligned}$$

$$N(\gamma) \propto \gamma^{-1}; \quad \gamma < \gamma_c \quad (21)$$

Since $s > 2$, in this case the peak energy $\gamma_{\text{peak}} = \gamma_{\text{inj}}$. When instead $\gamma_c > \gamma_{\text{inj}}$ (slow cooling), we have:

$$\begin{aligned} N(\gamma) &\propto \gamma^{-(s+1)}; & \gamma > \gamma_c \\ N(\gamma) &\propto \gamma^{-s}; & \gamma_{\text{inj}} < \gamma < \gamma_c \\ N(\gamma) &\propto \gamma^{-1}; & \gamma < \gamma_{\text{inj}}. \end{aligned} \quad (22)$$

For the assumed range of values of s , the peak energy in this case is $\gamma_{\text{peak}} = \gamma_c$.

2.10 Summary of free parameters

Our scheme needs the following parameters:

- the black hole mass M ;
- the accretion rate \dot{M}_{in} , or, equivalently, the disk luminosity in units of the Eddington one, $L_{\text{disk}}/L_{\text{Edd}}$;
- the bulk Lorentz factor Γ ;
- the initial separations of the colliding shells (in the internal shock case) or, more generally, the distance, in units of Schwarzschild radii, of the dissipation region;
- the “equipartition” parameters ϵ_e and ϵ_B
- the jet efficiency factor η_{jet} ;
- the slope s of the injected particle distribution.

The viewing angle θ is not considered as a free parameter, since we always assume $\Gamma \sim \delta$ and then $\theta \sim 1/\Gamma$. We have rather good observational constraints on several of these 9 parameters. For instance, $10 < \Gamma < 20$; R_{diss} is a few hundreds Schwarzschild radii; the (average) slope of the injected particle distribution is $s \sim 2.4$ – 2.5 ; the jet is slightly more powerful than the disk luminosity, leading to $\eta_{\text{jet}} \sim 0.2$ – 0.5 ; as mentioned, we have derived ϵ_B and ϵ_e for a number of blazars, and we can use these numbers in our scenario. In general, the most important parameters are thus M and \dot{M}_{in} , that are the leading quantities characterising our proposed scheme.

3 SIMPLE CONSEQUENCES

In this section we derive in an heuristic way a few simple consequences of our assumptions, leaving for the following sections a more detailed description, which requires more technical details.

• **BL Lac/FSRQ division** — The first consideration is, in itself, one of our assumptions: the BLR exists only when $L_{\text{disk}}/L_{\text{Edd}}$ is greater than some value, which we take equal to 3×10^{-3} . This immediately implies a division between FSRQs and BL Lac objects, defined as objects with and without broad emission lines, respectively.

• **Existence of “blue” FSRQs** — The BLR radius $R_{\text{BLR}} \propto L_{\text{disk}}^{1/2} \propto \dot{M}_{\text{in}}^{1/2}$, while the dissipation distance is $R_{\text{diss}} \propto M$. Therefore there is the possibility that relatively high mass objects, with relatively faint disk (but with $L_{\text{disk}} > L_c$) have jets preferentially dissipating beyond the BLR (see also Georganopoulos, Kirk & Mastichiadis 2001, Pian et al. 2006). The emitting electrons would suffer less radiative cooling, implying a large γ_{peak} and a “blue” SED. From Eq. 9 and Eq. 4 we have that $R_{\text{diss}} > R_{\text{BLR}}$ for

$$0.39M_9 < L_{\text{disk},45} < 0.81M_9^2 \left[\frac{a(\Gamma)}{300} \right]^2 \quad (23)$$

This defines a “triangular” region in the L_{disk} – M plane, as illustrated in Fig. 2.

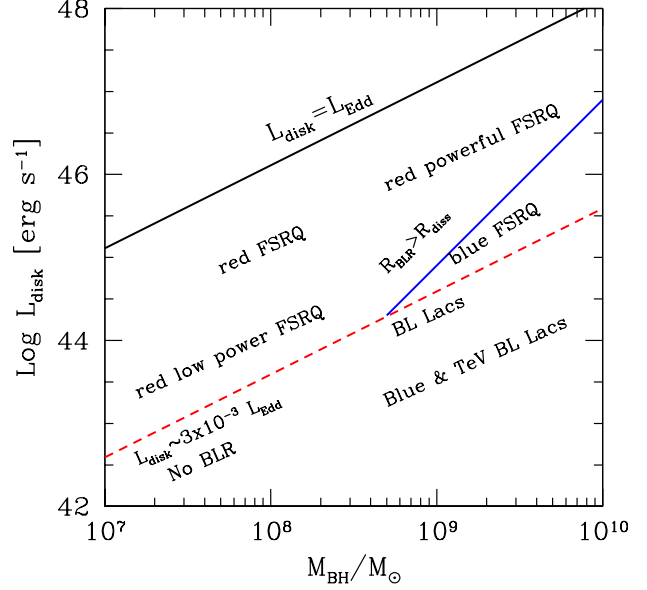


Figure 2. The disk luminosity vs black hole mass plane. Different blazar classes occupy different regions of this plane. The dashed line corresponds to a disk luminosity equal to a fraction of the Eddington one (for this figure we have used 3×10^{-3}). Below this line we assume that the broad line region does not exist, or it is very weak. Therefore BL Lac objects live below this line: “classic” BL Lac objects just below, and TeV BL Lacs at smaller still disk luminosities. According to our scenario, there is another important dividing line, corresponding to where $R_{\text{diss}} > R_{\text{BLR}}$ [for this figure we have used $a(\Gamma) = 300$]. Objects having a BLR, but whose jets preferentially dissipates beyond it, are “blue” quasars. If blazars can have relatively small black hole masses (i.e. even smaller than $10^8 M_\odot$), then there should be a population of relatively low power quasars, with a red spectrum.

• **Existence of “red” FSRQs at relatively low power** — This is a consequence of considering relatively small black hole masses. If FSRQs with –say– $M \sim 3 \times 10^7 M_\odot$ exist, then they have disk luminosities down to $L_{\text{disk}} \sim 1.2 \times 10^{43} \text{ erg s}^{-1}$; and similar jet powers (see Fig. 2). Dissipation takes place well within the (small) BLR, in regions of large U' implying small γ_{peak} and hence a red SED. The emitting regions would also have relatively large magnetic fields ($U_B \propto 1/M^2$, see Eq. 14), implying large U_B . The synchrotron self-Compton emission would then be relatively more important than the External Compton component.

• **The Compton dominance** — It is defined as the ratio of the inverse Compton to synchrotron luminosity L_C/L_s and corresponds to (for scattering in the Thomson regime)

$$\frac{L_C}{L_s} \sim \frac{U'_s + U'_{\text{ext}}}{U_B} \quad (24)$$

where the external radiation energy density U'_{ext} (in the comoving frame) is produced by the BLR and by the dusty torus, while U'_s is the synchrotron radiation energy density. In general, we expect that the Compton dominance is larger for FSRQs with $R_{\text{diss}} < R_{\text{BLR}}$. But since U_B is larger for smaller R_{diss} (smaller masses), while U'_{ext} is constant (for equal Γ), we expect that the Compton dominance is on average larger for larger masses.

In Fig. 2 we illustrate these simple points in the plane L_{disk} – M . The line dividing BL Lac objects from FSRQ is assumed to be at $L_{\text{disk}}/L_{\text{Edd}} = 3 \times 10^{-3}$, the radius of the broad line region corresponds to Eq. 4, and the dissipation radius assumes $a(\Gamma) =$

300. These values are indicative, but not certain, and there can be a substantial scatter. We recall that “red” and “blue” here mean that the synchrotron and inverse Compton peak frequencies have low or large values, respectively, but not that they are necessarily more or less Compton dominated. To make further predictions about the predicted SED as a function of M and \dot{M}_{in} , we must evaluate the Compton dominance in detail. This is done below.

4 ESTIMATING THE COMPTON DOMINANCE

In this section we show how it is possible, with a few reasonable assumptions, to derive the ratio between the inverse Compton to synchrotron luminosity. This parameter, called Compton dominance, will determine in what region of the M – \dot{M}_{in} plane we can find γ –ray bright sources (and viceversa where are the γ –ray dim blazars).

In the Appendix we show the importance of the so-called Comptonization y parameter, and how it can be calculated. We define it as

$$y \equiv \sigma_T \Delta R' \int \gamma^2 N(\gamma) d\gamma \quad (25)$$

In the Appendix we also show that the comoving synchrotron and self-Compton radiation energy densities can be expressed as $U'_s = yU_B$ and $U'_{\text{SSC}} = y^2 U_B$, while the external Compton energy density is $U'_{\text{EC}} = yU'_{\text{ext}}$. The asymptotic values of y are:

$$\begin{aligned} y &\sim \frac{1}{2} \left[1 + \frac{4\epsilon_e \epsilon_A}{\epsilon_B} \right]^{1/2} - \frac{1}{2}; & \frac{U'_{\text{ext}}}{U_B} &\ll 1 \\ y &\sim \frac{\epsilon_e \epsilon_A}{\epsilon_B} \frac{U_B}{U'_{\text{ext}}}; & \frac{U'_{\text{ext}}}{U_B} &\gg 1 \end{aligned} \quad (26)$$

where we have assumed that the scattering process occurs in the Thomson regime. In this regime the ratio between the inverse Compton and the synchrotron luminosities can be approximated as

$$\frac{L_c}{L_s} = \frac{U'_{\text{syn}}}{U_B} + \frac{U'_{\text{ext}}}{U_B} = y + \frac{U'_{\text{ext}}}{U_B} \quad (27)$$

The first term on the RHS controls the relative importance of the SSC component, while the second measures the relative importance of the EC component. They are not independent, because the value of y is in turn controlled by the (U'_{ext}/U_B) ratio, as shown by Eq. 26.

Isolating the EC dominance we can focus on FSRQs with $R_{\text{diss}} < R_{\text{BLR}}$:

$$\frac{L_{\text{EC}}}{L_s} = \frac{U'_{\text{ext}}}{U_B} \propto \frac{M^2}{\dot{M}_{\text{in}}} \Gamma^4 \frac{[a(\Gamma)]^2}{\epsilon_B} \propto \frac{M}{L_j/L_{\text{Edd}}} \Gamma^4 \frac{[a(\Gamma)]^2}{\epsilon_B} \quad (28)$$

where we made use of Eq. 6, Eq. 9 and Eq. 14. This implies that FSRQs of the same mass and increasing \dot{M}_{in} form a sequence of increasing power and *decreasing* Compton dominance. On the other hand FSRQs of increasing mass and constant L_j/L_{Edd} form a sequence of increasing power and increasing Compton dominance. Note also the strong dependence on the bulk Lorentz factor. FSRQs of equal masses and accretion rates can form a sequence of increasing power and increasing Compton dominance by having slightly different values of Γ .

The SSC over synchrotron power ratio is simply y . When the EC emission is unimportant, $y \sim (\epsilon_e \epsilon_A / \epsilon_B)^{1/2}$, greater than unity when $\epsilon_e > \epsilon_B / \epsilon_A$ (Eq. 26).

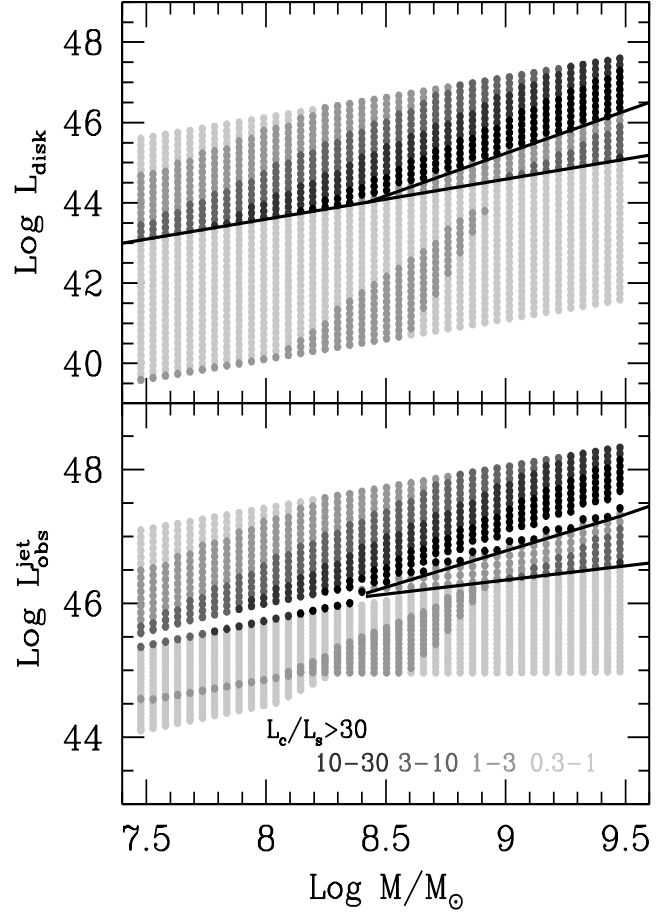


Figure 3. The disk accretion luminosity (top panel) and the observed bolometric jet emission (bottom panel), as a function of black hole mass. The bulk Lorentz factor is assumed to be 15 for all cases, while we have assumed $a(\Gamma) = 300$ for FSRQs and 100 for BL Lacs. The solid lines on bot panels correspond to $L/L_{\text{Edd}} = 3 \times 10^{-3}$ and on to the region where $R_{\text{diss}} > R_{\text{BLR}}$. The different grey levels correspond to different “Compton dominance”, i.e. different L_c/L_s ratios.

5 RESULTS

The results of our scheme, for the set of chosen parameters, are shown in Fig. 3 and Fig. 4. In this figures the different grey levels corresponds to different Compton dominance values, as labelled. Consider first Fig. 3. The top panel is equivalent to Fig. 2. Below the diagonal line $L_{\text{disk}}/L_{\text{Edd}} = 3 \times 10^{-3}$ we have BL Lacs, above the line we have FSRQs.

The solid lines divide the plane in three regions: in region I, above the solid line $L_{\text{disk}}/L_{\text{Edd}} = 3 \times 10^{-3}$, we have the FSRQs. Below this line, in region II, we have BL Lac objects. In region III, limited by the two solid lines, we have the “blue” FSRQs.

The Compton dominance in region I increases for increasing mass and decreases for increasing L_{disk} for objects with the same mass, as described by Eq. 28 [for $a(\Gamma)$ constant]. In region II the Compton dominance, determined by $y \sim (\epsilon_e \epsilon_A / \epsilon_B)^{1/2}$, is varying much less and is of order unity in the entire region. In region III we have the same trend as in region I, but with a lower Compton dominance value, determined partly by SSC emission (scaling with y) and partly by the torus external IR photons.

The bottom panel shows the observed bolometric luminosity

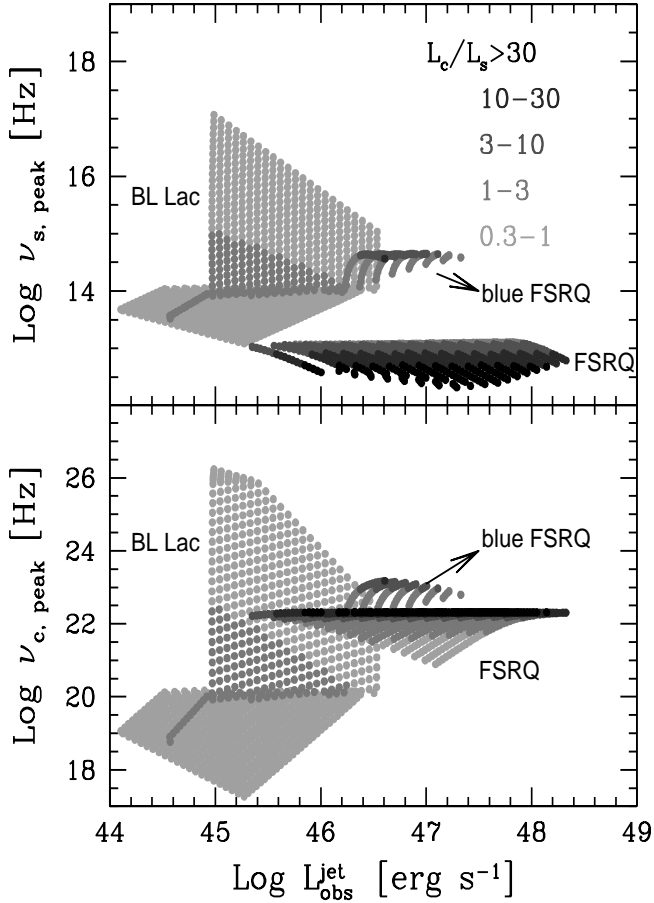


Figure 4. The peak synchrotron frequency $\nu_{s,\text{peak}}$ (top) and the peak Compton frequency $\nu_{c,\text{peak}}$ (bottom) as a function of the observed jet luminosity. As in Fig. 3, different grey levels indicate different Compton dominance values.

produced by the jet as a function of the mass. In this plane objects belonging to regions II and III partially overlap, since we can have “blue” FSRQs slightly less luminous than BL Lacs. This effect is due to the fact that in this illustrative figure we have assumed that the dissipation region of BL Lac objects has $a(\Gamma) = 100$, while we use $a(\Gamma) = 300$ for FSRQs. Some BL Lac objects, therefore, although lacking the BLR, are slightly more efficient (larger ϵ_A) than “blue” FSRQs, simply because they are more compact. This also means that their magnetic field is relatively larger, resulting in a less Compton dominated source.

In Fig. 4 we show the predicted peak frequency of the synchrotron flux (top panel) and of the IC emission (bottom). Again, different grey levels correspond to different Compton dominance values. Note that the range of $\nu_{s,\text{peak}}$ and $\nu_{c,\text{peak}}$ values is much broader for BL Lac objects than for FSRQs. This is the consequence of two facts: first, the dependence of γ_{peak} on U' is stronger for BL Lacs than for FSRQs ($\gamma_{\text{peak}} \propto U'^{-1}$ vs $\gamma_{\text{peak}} \propto U'^{-1/2}$ respectively); secondly, the energy density of the external seed photons is constant, as implied by assuming $R_{\text{BLR}} \propto L_{\text{disk}}^{1/2}$ and a constant Γ : thus when the external radiation energy density dominates, it implies a quasi-constant γ_{peak} , that in turn makes $\nu_{s,\text{peak}}$ and $\nu_{c,\text{peak}}$ to vary in a small range.

Fig. 4 shows that the maximum values of $\nu_{s,\text{peak}}$ and $\nu_{c,\text{peak}}$

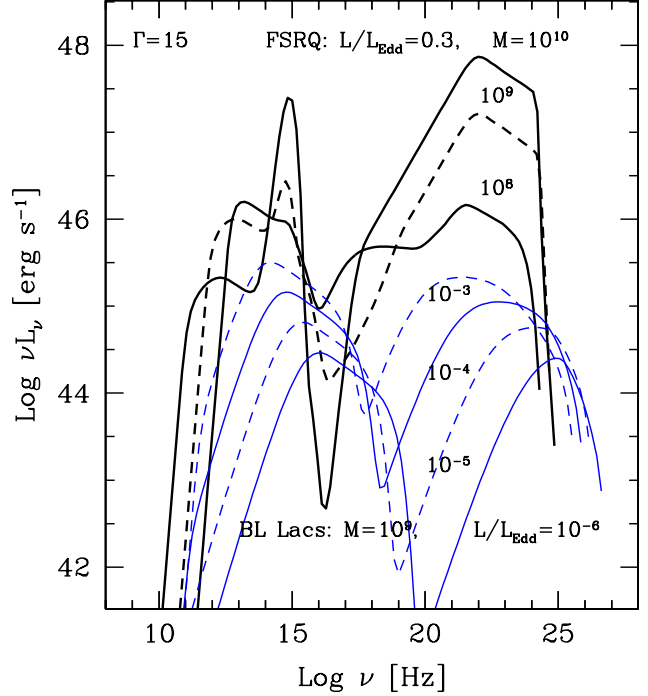


Figure 5. Predicted SED as a function of black hole mass and disk luminosities. For FSRQ (top three thick lines) we have assumed a constant L/L_{Edd} ratio (equal to 0.3) and different black hole masses. For BL Lacs, instead (lower four lines thin lines), we have shown SEDs corresponding to a black hole mass of $10^9 M_\odot$ and different L/L_{Edd} values, as labelled.

of FSRQs have a sharp boundary. This is due to the following. When the BLR radiation energy density dominates the cooling, we have

$$\nu_{s,\text{peak}} = 3.6 \times 10^6 \Gamma B \gamma_{\text{peak}}^2 = \frac{3.6 \times 10^6 \Gamma B}{(17/12) U_{\text{BLR}} \Gamma^2 + U_B} = \frac{2.7 \times 10^{13} \Gamma B}{0.944 \Gamma^2 + B^2} \text{ Hz} \quad (29)$$

where we have used Eq. 6 and Eq. 19. The maximum $\nu_{s,\text{peak}}$ is reached for $B^2 = 0.944 \Gamma^2$. In our case, since $\Gamma = 15$, we have $\nu_{s,\text{peak}} = 1.4 \times 10^{13} \text{ Hz}$.

Blue FSRQs, on the other hand, suffer much less cooling (they dissipate beyond the BLR) and consequently their γ_{peak} and $\nu_{s,\text{peak}}$ are larger, explaining the existence of the gap (in $\nu_{s,\text{peak}}$) of the two populations.

It is worth to stress that blazars will not all have the same value of Γ (that can change even in a single source). The sharp boundaries described above and shown in Fig. 4 will disappear once we allow for a distribution of Γ -values.

5.1 Predicted SED

In Fig. 5 we show several predicted SEDs of FSRQs and BL Lac objects. For FSRQs the spectra correspond to objects with the same ratio $L_{\text{disk}}/L_{\text{Edd}} = 0.3$ and different masses, while for BL Lacs we have the same mass ($10^9 M_\odot$) and different $L_{\text{disk}}/L_{\text{Edd}}$ ratios. In agreement with Fig. 3, FSRQs are more Compton dominated as the mass (and then the bolometric luminosity, for constant $L_{\text{disk}}/L_{\text{Edd}}$) increases, with almost constant peak frequencies. Note that, increasing the mass, the IC luminosity increases, while the synchrotron component decreases. This can be understood recalling that $L'_s \propto y U_B R_{\text{diss}}^2$ and inserting the appropriate scaling of U_B (Eq. 14) and y (Eq. 35), yielding $L'_s \propto \epsilon_e \epsilon_B L_j^2 / R_{\text{diss}}^2 \propto$

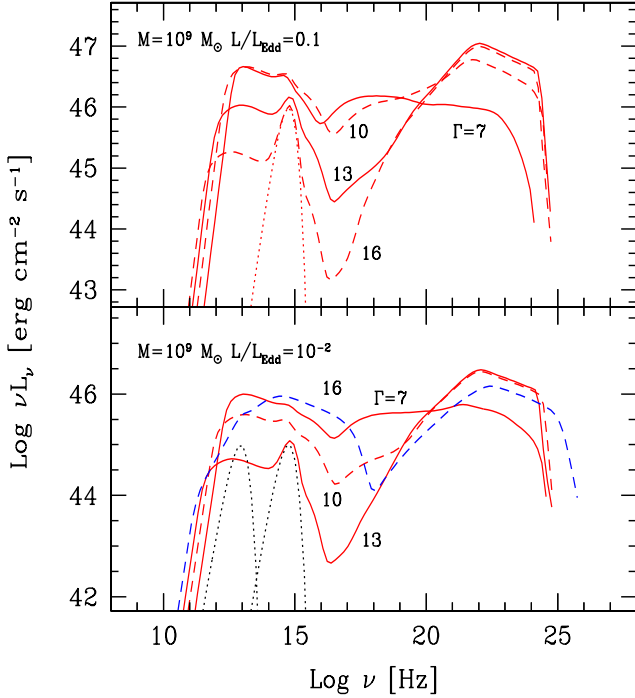


Figure 6. Predicted SED as a function of the bulk Lorentz factor for a fixed black hole mass ($10^9 M_\odot$) and for $L/L_{\text{Edd}} = 0.1$ (top panel) and $L/L_{\text{Edd}} = 10^{-2}$ (bottom panel). For the latter case, note the SED of the $\Gamma = 16$ case, remarkably different from the others. In this case $R_{\text{diss}} > R_{\text{BLR}}$ and no external BLR photons contribute to the radiative cooling. There is instead a contribution coming from the torus. The reduced cooling implies a large γ_{peak} , making the SED similar to the one of a blue BL Lacs. However, the broad lines do exist, and the objects would be classified as “blue” quasars (with a synchrotron peak frequency $\nu_{\text{peak}} \sim 10^{15}$ Hz).

$\epsilon_e \epsilon_B (L_{\text{disk}}/L_{\text{Edd}})^2$. Therefore, for a constant ratio $L_{\text{disk}}/L_{\text{Edd}}$, the synchrotron luminosity $L_s \propto \epsilon_e \epsilon_B$ which we assume to scale as $L_j^{-(0.4+0.25)}$ (see Eq. 17 and Eq. 18).

The spectral indices in the \sim GeV (α_γ) and X-ray (α_X) bands anti-correlate: at low luminosities we have a steep α_X (due to the tail of the synchrotron emission) and a hard α_γ (due to a still rising SSC spectrum), while at large powers we have a flat α_X (due to the low energy part of the EC spectrum) and a steep α_γ (due to the high energy tail of the same component). This is in agreement to what observed (e.g. Comastri et al. 1997).

The series of SED in Fig. 5 resembles the phenomenological sequence of Fossati et al. (1998). In order to reproduce the observed increase of the Compton dominance with the total power for FSRQs we assume the same $L_{\text{disk}}/L_{\text{Edd}}$ and change the black hole mass. This choice is dictated by the fact that, in the present scheme, the Compton dominance increases with the mass (as clearly visible in Fig. 3). Fixing the mass and increasing the disk luminosity, instead, would have the effect to *reduce* the Compton dominance, contrary to the observed trend. Low power BL Lac objects, instead, display in the blazar sequence a more or less constant Compton dominance and we can reproduce this branch of the blazar sequence using a fixed (large) black hole mass and varying the accretion rate.

6 CHANGING PARAMETERS

In the previous section we have shown the SED expected for different values of the mass and accretion rate. Here we briefly discuss the consequences of changing some other input parameters of the model.

- Changing the bulk Lorentz factor Γ . In Fig. 6 we show the predicted SED as a function of the bulk Lorentz factor for $L/L_{\text{Edd}} = 0.1$ (top panel) and $L/L_{\text{Edd}} = 10^{-2}$ (bottom panel). The black hole mass is kept constant ($M = 10^9 M_\odot$). The bulk Lorentz factors are in the range 7–16. It can be seen that even small changes of Γ imply large changes in the observed SEDs, as described by Eq. 28, as long as $R_{\text{diss}} < R_{\text{BLR}}$. Since we have assumed $a(\Gamma) \propto \Gamma^2$ for this test, we have $L_c/L_s \propto \Gamma^8$. The top panel shows a monotonic sequence, since for all Γ we have $R_{\text{diss}} < R_{\text{BLR}}$. The bottom panel, instead, shows the case of a “blue” quasar: for the largest adopted Γ , in fact, we have $R_{\text{diss}} > R_{\text{BLR}}$, and the external photons contributing to the EC spectrum are coming from the torus only, contributing to the comoving radiation energy density according to Eq. 8. This implies a slower electron cooling, a larger γ_{peak} and consequently larger peak frequencies. Observers would however detect the broad emission lines in this blazars, classifying it as a “blue” FSRQ, with a synchrotron peak frequency $\nu_{\text{peak}} \sim 10^{15}$ Hz.

- Changing ϵ_e and ϵ_B . There are two different regimes: when the external seed photons dominate, ϵ_e controls the total produced luminosity, but not the Compton dominance, which is instead proportional to ϵ_B^{-1} (see Eq. 28). When instead the high energy spectrum is dominated by the SSC flux, the Compton dominance is proportional to $(\epsilon_e/\epsilon_B)^{1/2}$ (as in Gamma Ray Burst afterglows).

- Changing R_{diss} . Although we always assume $R_{\text{diss}} \propto M$, we can change the constant of proportionality $[a(\Gamma)]$. As a rule, if we are inside the BLR, a smaller R_{diss} means a larger magnetic field, and thus a smaller Compton dominance (see Eq. 14; Eq. 28). Also, increasing $a(\Gamma)$, makes the case $R_{\text{diss}} > R_{\text{BLR}}$ more probable, enlarging the parameter space for blue quasars.

- Changing s . Besides changing the predicted slope above the peaks, it changes ϵ_A for objects emitting in slow cooling: the steeper s , the less efficient the source (small ϵ_A). Since the majority of blazars emitting in the slow cooling regime are the ones with no BLR (and torus), a steeper s also means less (self-) Compton dominance.

- Changing η_j . This parameter acts as a normalisation: larger η_j means that the jet is more powerful overall. Keeping all other parameter constant, increasing η_j increases the value of the magnetic field, and therefore it decreases the Compton dominance when the external seed photons dominate the radiation energy density. When they do not, changing η_j has no effect on the Compton dominance.

7 CAVEATS

Our proposed scenario is necessarily highly idealised and is aimed at describing the *averaged* behaviours of different classes of blazars and also of a single blazars that can have different states. In this section we therefore try to summarise a few caveats that should be kept in mind.

- Leptonic model. Probably the most basic assumptions of ours is that the emission comes from the acceleration and the radiative cooling of leptons, and we have neglected the possible presence of relativistic hadrons (Mannheim 1993, Aharonian 2000, Mücke et al

2003). While the variability patterns observed in some (admittedly, a few) blazars seem to favour the leptonic model, the hadronic scenario is not ruled out yet.

- **Single zone emission region.** We have assumed that most of the SED is produced in a single region, characterised by a single valued and uniform magnetic field, with a single particle distribution, and so on. This is the most commonly adopted simplification, that received support from the few cases in which we could see co-ordinated variability in different energy bands, but consider that i) there surely are several emitting regions, contributing differently to the entire SED. The region producing the radio flux, for instance, is surely much larger than what we consider here, and could contribute (by its SSC flux) to the X-ray radiation; ii) the jet could be structured, composed by a fast spine surrounded by a slower sheath-layer, as envisaged in Ghisellini, Tavecchio & Chiaberge (2005). Some support in this sense for TeV BL Lac objects comes from the fact that these sources have “slow” VLBI knots, often moving sub-luminally (Piner & Edwards 2004, Piner, Pant & Edwards 2008 and references therein), and from direct observations of some radio edge-brightening (Giroletti et al. 2004, 2006).

- **A different R_{diss} for BL Lacs.** Associated to the previous point is the possibility that not all blazars have the same $a(\Gamma)$ appearing in the relation $R = a(\Gamma)R_s$. We have in fact assigned, to BL Lac objects, a different $a(\Gamma)$ than in FSRQs, but the real value could be different from what we have adopted.

- **Different bulk Lorentz factors Γ for different classes of objects.** There is the need, for TeV BL Lacs, of a very large Γ , larger than for other blazars. The reasons are the very short variability timescales observed for the TeV flux (3 minutes in PKS 2155–304, Aharonian et al. 2007; see the implications in Begelman, Fabian & Rees 2008 and models in Ghisellini & Tavecchio 2008); and the necessity, in single zone SSC models, to account for the large separation, in frequency, of the two peaks of the SED (e.g. Konopelko et al. 2003; Tavecchio, Maraschi & Ghisellini 1998).

- **The relation $\gamma_{\text{peak}}(U)$.** This seems well obeyed by all observed sources of low–medium power, while for powerful objects we have a larger scatter. There is a branch at large U for which $\gamma_{\text{peak}} \propto U^{-1}$ instead of $\propto U^{-1/2}$ (see Celotti & Ghisellini 2008).

- **Thomson vs Klein–Nishina scattering regime.** Our estimates assume that the inverse Compton process occurs in the Thomson regime, so only for γ_{peak} not extremely large. We can estimate how large by the following argument. If the EC process is important, then cooling is efficient, $\gamma_{\text{peak}} < 10^3$ – 10^4 and the bulk of scatterings indeed occurs in the Thomson regime. When instead the SSC process is the main producer of high energy photons, then we may neglect Klein Nishina effects when $\gamma_{\text{peak}} h\nu'_s / (m_e c^2) < 1$, where $\nu'_s \sim 3.6 \times 10^6 B \gamma_{\text{peak}}^2$ is the synchrotron peak frequency in the co-moving frame. Therefore the Klein–Nishina regime is unimportant if

$$\gamma_{\text{peak}} < \left(\frac{m_e c^2}{3.6 \times 10^6 B h} \right)^{1/3} \sim 3.2 \times 10^4 B^{-1/3} \quad (30)$$

This corresponds to observed synchrotron peak frequencies $\nu_s \sim 3.7 \times 10^{15} B^{1/3} \delta$ Hz and self Compton frequencies $\nu_c = \gamma_{\text{peak}}^2 \nu_s \sim 3.8 \times 10^{24} B^{-1/3} \delta$ Hz $\sim 15.6 B^{-1/3} \delta$ GeV. With $\delta \sim 10$ and $B \sim 0.1$ G, blazars with Compton peak energies below ~ 70 GeV should still be in the Thomson limit.

- **SED based on flares.** Our scenario is inevitably built upon what we already know, and this is mostly limited by the sensitivity of EGRET. Therefore, the complete SED we could construct, from the radio to the GeV band, are most likely associated to sources in

very active (γ -ray) states, and might not be indicative of the more standard, but more persistent, blazar spectrum.

- **Viewing angle.** The models presented here assume that the jet is observed with a small angle $\theta \sim 1/\Gamma \sim 4$ deg. According to the current unification schemes, besides these highly beamed sources a large number of moderately less beamed blazars should exist ($\theta \sim 4$ – 7 deg), for which the non-thermal continuum of the jet is less amplified and thus less luminous. An effective way to distinguish between these sources and true low power FSRQs is through the level of the optical emission, that in the misaligned objects should be dominated by the “naked” thermal disk emission (see also Landt et al. 2008).

8 IMPLICATIONS FOR COSMIC EVOLUTION

The association of different classes of blazars with the mass of the black hole and with the accretion rate can have important effects on the predicted evolution of blazars.

Black hole of large masses ($M > 10^9 M_\odot$) are rare, while black holes of smaller masses are more common (at any redshift). If the accretion rate in blazars evolves in redshift, as indicated by the redshift evolution of radio-quiet quasars, we should have larger accretion rates in the past. As a consequence, blazars whose accretion rate is less than a critical value – sources that we associate with BL Lac objects – should become rarer in the past, implying a negative evolution. On the contrary, FSRQs should be more common in the past, since a larger fraction of massive black holes accretes at rates larger than the critical one.

At large redshifts, when the black hole is fully accreting, we have powerful disk and jets and a BLR located at relatively large distances. These are the conditions to have a powerful, Compton dominated, FSRQ. The same object will lower its accretion rate with time, the disk becomes a less efficient radiator, the BLR shrinks, and there should be the possibility to have a transitional object, with emission lines of moderate luminosity, and with a SED that can be produced sometimes within, sometimes outside, the BLR region (i.e. the red/blue FSRQ case in Fig. 2). When the accretion rate decreases below the critical value (i.e. $L_i/L_{\text{Edd}} < 3 \times 10^{-3}$, the accretion changes mode, becoming radiatively inefficient. The corresponding BLR (if it exists at all) becomes weak and very close to the black hole. Jet dissipation occurs always beyond the BLR, and the source becomes a BL Lac object. Synchrotron and SSC are the main emission processes, and the position of the corresponding peaks in the SED depends on the amount of radiative cooling (bluer for less cooling).

These simple ideas are in line with the scenario proposed by Cavaliere & D’Elia (2002), in which blazars are born initially powerful (high accretion rate), and transform themselves into BL Lac objects when the accretion rate decreases. The evolution of blazars as a whole should be the same of radio-quiet quasars (Maraschi & Rovetti 1994), but with black hole masses larger than $\sim 3 \times 10^7 M_\odot$ (if this is the real limit to have a radio loud object). SED-wise, the evolution is more complicated, since for low masses and intermediate accretion rate, a FSRQ can be blue ($R_{\text{diss}} > R_{\text{BLR}}$), but still have visible broad lines.

9 CONCLUSIONS

We have proposed an extension of the scheme based on the so-called “blazar sequence”, taking advantage from the new facts and

ideas discovered or suggested since the “old” blazar sequence was published. Our aim is not to propose a new model or scenario for blazars, but rather to view them from a different point of view, enabling a different perspective. Technically, we pass from a one-parameter (observed bolometric luminosity) to a two-parameter sequence (M and \dot{M}_{in}), but, more physically, we try to link the properties of the jet to the main properties of the accretion disk. To do this, we had to make a number of simplifying assumptions, that we think are rather reasonable or even supported by strong observational evidence, but of course there remains some uncertainties. In addition to this, we stress that, at this stage, we can only (and necessarily) describe *averaged properties* of blazars and some *trends*. But the link between the two fundamental parameters (M and \dot{M}_{in} , or, rather, L_{disk} and M) characterising the new sequence and the blazar SED makes our proposal perfectly testable (and falsifiable). The main results are:

- Blue quasars may exist. If the dissipation region of the jet is beyond the broad line region, the radiation energy density seen in the comoving frame is not large, resulting in less electron cooling, and thus large electron energies. This in turn results in large synchrotron and inverse Compton peak frequencies. This might happen for large black hole masses and intermediate accretion rates (for small \dot{M} there are no broad lines anymore, and the objects become a BL Lac, for large \dot{M} the radius of the BLR is large, making it difficult that the jet produces most of its luminosity beyond it). If the dissipation region is related to the value of the bulk Lorentz factor, as in the internal shock scenario, then an additional requirement is that Γ should be relatively large. Note that the region of the parameter space corresponding to blue quasars is not large, and its extension depends upon Γ and the relation between the radius of the BLR and the disk luminosity. At this stage, it is then difficult to quantify more precisely how many blue emission line blazars there are.
- Low power blazars (red FSRQs; red and blue BL Lacs) should exist. They correspond to blazars associated with low mass black holes. The blue BL Lacs, corresponding to smaller accretion rates and hence smaller jet powers, can be missed more easily (than red blazars) in flux limited samples. It is possible that this effect can account for the large number of red blazar in deep flux limited samples (see e.g. Padovani et al. 2007) especially if blazars with black holes of small masses are more numerous. To demonstrate this, we of course need detailed simulations, that we leave for future work.
- Red low power blazars should exist. Again they simply correspond to objects with black holes of relatively small masses and relatively large accretion rates, hence with a “normal” broad line region. Low power red sources should be easily distinguished from the powerful misaligned counterparts (expected to have a similar SED) since in these latter objects the powerful disk emission is expected to dominate over the non-thermal continuum in the optical-UV region (see Landt et al. 2008).
- Not only the power of jets, but also the SED that they produce is linked with M and \dot{M}_{in} . This is the most important result of our study.

To confirm or falsify our ideas we need to know the SED, the mass of the black hole, and the disk luminosity (or, equivalently, the luminosity of the broad emission lines). We hope to soon enter in the “*GLAST* era”, greatly helping to determine the blazar bolometric luminosity and their high energy SED. If the blazar sample of EGRET counts ~ 60 objects, a improvement of a factor 10 in sensitivity means roughly that *GLAST* will detect ~ 2000 blazars. Assuming that *Swift* can observe, simultaneously and with its op-

tical and X-ray telescopes, 1/10 of them, we can have a sample of ~ 200 blazars with an optical to GeV *simultaneous* coverage. This means a large improvement in number, and a huge improvement in quality, of our knowledge. These blazars can form a “golden” sample for ground based follow up, aiming to measure (if there are) the luminosity the broad emission lines and estimate the mass of the central black hole. With these information, we can easily confirm or reject the new blazar sequence we propose.

ACKNOWLEDGEMENTS

We thank Annalisa Celotti and Laura Maraschi for useful discussions, and the anonymous referee for helpful comments.

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Appendix

The Comptonization y parameter

Our method uses the fact that we “know” the total radiation energy density produced in the dissipation region, since it corresponds to the fraction of energy lost by the electrons in one light crossing time: $U'_r = \epsilon_A U_e$. This radiation energy density U'_r is the sum of the synchrotron and inverse Compton emission³.

Consider first the synchrotron emission, with a corresponding cooling rate given by $\dot{\gamma}_s = (4/3)\sigma_T c U_B \gamma^2 / (m_e c^2)$. Neglecting self-absorption, the total (comoving) synchrotron luminosity is

$$L'_s = \pi r^2 \Delta R' m_e c^2 \int N(\gamma) \dot{\gamma}_s d\gamma \quad (31)$$

We now divide and multiply by $n \equiv \int N(\gamma) d\gamma$ and define $\tau \equiv n \Delta R' / c$. We can also write L'_s as $U'_s \pi r^2 c$. We then have

$$U'_s = U_B \frac{4}{3} \tau \langle \gamma^2 \rangle \equiv y U_B \quad (32)$$

where the last equivalence corresponds to define the Comptonization parameter $y \equiv (4/3)\tau \langle \gamma^2 \rangle$. Assuming that the scattering process occurs in the Thomson regime we can analogously set $U'_{SSC} = y U'_s = y^2 U_B$, and $U'_{EC} = y U'_{ext}$. The sum of these components constitutes U'_r :

$$U'_r = U'_{syn} + U'_{SSC} + U'_{EC} = y U_B + y^2 U_B + y U'_{ext} \quad (33)$$

Dividing both parts by U_B we obtain an equation dependent on the microphysical parameters ϵ_B , ϵ_e and ϵ_A (defined in §2.7, see Eqs. 14, 15), and dependent on L_j only through the ratio U'_{ext}/U_B :

$$\frac{U'_r}{U_B} = \frac{\epsilon_A \epsilon_e}{\epsilon_B} = y^2 + y \left(1 + \frac{U'_{ext}}{U_B} \right) \quad (34)$$

The solution is:

$$y = \frac{1}{2} \left\{ \left[\left(1 + \frac{U'_{ext}}{U_B} \right)^2 + \frac{4\epsilon_e \epsilon_A}{\epsilon_B} \right]^{1/2} - \left(1 + \frac{U'_{ext}}{U_B} \right) \right\} \quad (35)$$

For U'_{ext}/U_B much smaller or greater than unity we have the limiting cases of Eq. 26.

Finding ϵ_A

To find ϵ_A , consider an injected relativistic electron distribution that has a power law form, $Q(\gamma) = Q_0 \gamma^{-s}$, between some γ_1 and γ_2 . The fraction ϵ_A of radiated energy (in one light crossing time) can be approximated as

$$\epsilon_A = \frac{\int_{\gamma_1}^{\gamma_2} \gamma^{1-s} d\gamma}{\int_{\gamma_1}^{\gamma_2} \gamma^{1-s} d\gamma} \sim \left(\frac{\gamma_1}{\gamma_{peak}} \right)^{s-2}; \quad s > 2 \quad (36)$$

The value of γ_{peak} depends upon $U' = U_B + U'_s + U'_{ext}$ (Eq. 19). In particular, the synchrotron radiation energy density

³ U'_r should not be confused with U' of Eq. 19, which is the magnetic plus radiative energy density available for efficient scattering and contributing to the cooling.

depends upon y (Eq. 33), i.e. it depends on ϵ_A itself. Despite this circularity problem, we can solve the system iteratively, until convergence (obtained in a few cycles).